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IMPROVED LIFE SUPPORT CAPABILITY IN THE MK 11 SEMI-CLOSED CIRCUIT UBA BY MODIFICATION OF THE CARBON DIOXIDE ABSORBENT CANISTER

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During a series of three saturation dives performed at the U.S. Navy Experimental Diving Unit, experiments were undertaken to compare the CO_2 scrubbing characteristics of two new Mark 11 CO_2 absorbent canisters with the standard canister configuration, and to investigate the ability of each system to support sustained, heavy work in cold water to depths of 650 FSW.

Canister duration studies were performed on the three CO_2 absorbent (OVER)

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canister configurations at depths of 450 and/or 650 FSW. When compared to standard MK 11 canister performance, the central heated core configuration with Koegel valves (FC 979A) demonstrated markedly longer canister duration at 450 FSW, but only slight improvement at 650 FSW. However, work of breathing and inspired gas temperatures were greatly improved at both depths. The triple pass canister configuration demonstrated improved duration but unacceptably high breathing resistance.

Other life support characteristics such as thermal protection, inspired gas temperature, and PO_2 were adequate to depths of 650 FSW. The large scatter in canister breakthrough data coupled with limited sample size made it difficult to establish high-confidence operational limits for the Mark 11 UBA in any of the tested configurations, although significant overall advantages were demonstrated for the central heated core canister configuration (FC 979A).

ABSTRACT

During a series of three saturation dives performed at the U.S. Navy Experimental Diving Unit, experiments were undertaken to compare the CO_2 scrubbing characteristics of two new Mark 11 CO_2 absorbent canisters with the standard canister configuration, and to investigate the ability of each system to support sustained, heavy work in cold water to depths of 650 FSW.

Canister duration studies were performed on the three CO_2 absorbent canister configurations at depths of 450 and/or 650 FSW. When compared to standard MK 11 canister performance, the central heated core configuration with Koegel valves (FC 979A) demonstrated markedly longer canister duration at 450 FSW, but only slight improvement at 650 FSW. However, work of breathing and inspired gas temperatures were greatly improved at both depths. The triple pass canister configuration demonstrated improved duration but unacceptably high breathing resistance.

Other life support characteristics such as thermal protection, inspired gas temperature, and P_{O_2} were adequate to depths of 650 FSW. The large scatter in canister breakthrough data coupled with limited sample size made it difficult to establish high-confidence operational limits for the Mark 11 UBA in any of the tested configurations, although significant overall advantages were demonstrated for the central heated core canister configuration (FC 979A).

INTRODUCTION

The Mark 11 semi-closed mixed gas UBA and associated equipment was originally designed to provide complete life support and thermal protection for saturation divers to operate for up to four hours in 28°F (-2.2°C) water to depths of 850 FSW. The Mark 11 diver is tethered to a diver support facility by an umbilical which supplies breathing gas, hot water, and electrical connections. Hot water is routed through a breathing subsystem (Figure 1) where it warms a canister containing a carbon dioxide absorbent bed, and then to a thermal protection garment, the Mark 16 or NRV hot water suits.

During normal semi-closed circuit operation, breathing gas from the umbilical passes through an absolute pressure regulator block into an inhalation bag, and then through a hose connection to an oronasal face mask. Exhaled gas passes from the oronasal mask via a hose to an exhalation bag. From the exhalation bag, most of the exhaled gas flows through the CO_2 removal canister to the inhalation bag where it is mixed with incoming gas from the umbilical, and subsequently rebreathed. A portion of the exhaled gas does not pass through the canister but is exhausted to the water through an attitude sensitive exhaust valve (cardioid valve).

Diver safety features include two-way communication equipment, a P_{O_2} sensor, and switchover indication equipment. If umbilical gas supply pressure drops to a low level, the absolute pressure regulator admits breathing gas from a small emergency supply in the back-pack. If the breathing bags or canister flood, the diver can switch to open circuit demand with umbilical, or for a short time, emergency gas supply. Therefore, a normal operating mode and three back-up modes are available to the diver (Figure 2).

A number of parameters effect the ability of a diver to perform sustained work at depth while diving with this type of UBA. One of the most important of these parameters is the P_{CO_2} in the inspired gas. The P_{CO_2} is dependent upon gas flow rates, CO_2 absorbent efficiency, and the rate of CO_2 production by the exercising diver. A previous evaluation of the Mark 11 UBA in four feet of water demonstrated that the CO_2 absorbent canister appeared to absorb CO_2 efficiently for up to seven hours during prolonged moderate work in cold water (1). However, gas flow rates through the UBA during this study were so high (up to 16.4 actual lpm) that much of the CO_2 produced by the exercising diver bypassed the canister, and was exhausted through the cardioid valve.

Subsequent manned Mark 11 UBA studies at depths between 310 and 450 FSW demonstrated inadequate carbon dioxide scrubbing characteristics in 35°F water (2). In order to improve the life support capabilities of the Mark 11, two new canister prototypes which had shown promise in unmanned testing were chosen to undergo manned evaluations to depths of 650 FSW along with the standard canister during a series of three saturation dives at the Navy Experimental Diving Unit.

METHODS

Three saturation dives with depth duration profiles of 1000 FSW for 29 days, 650 FSW for 23 days, and 1800 FSW for 37 days, were performed in the Ocean Simulation Facility of the Navy Experimental Diving Unit. Each dive involved six male divers in good physical condition, who were conditioned for 6 to 8 weeks prior to the dives by running up to 7 km per day, and pedaling up to 200 watts for 10 minutes daily on a pedal ergometer. One of the divers participated in two of the dives.

The experiments were divided into two phases; the first phase consisted of canister duration studies, and the second phase consisted of graded exercise studies. Each of the three canister configurations as shown in Figure 3 was tested at 650 FSW. The central heated core canister configuration was also tested at 450 FSW. This configuration included replacement of the Mark 11 mask mushroom valves with low resistance Koegel valves, and was designated Field Change 979A. The standard canister had been tested previously at 450 FSW (2).

Breathing gas mixture was 88/12 helium-oxygen at 450 FSW, and 95/5 helium-oxygen at 650 FSW. Rig flow rates were adjusted for an average diver oxygen consumption ($\dot{V}_{O_2}$) of 2.0 lpm with a maximum P_{O_2} of 1.6 ATA, and a minimum P_{O_2} of 0.4 ATA. A number 13 orifice was used to provide minimum gas loss through the cardioid valve. Canisters were packed with 3.0 to 3.5 kg of High Performance Sodasorb (W. R. Grace Co.) just prior to each canister duration study.

Gas samples from the canister outlet, canister inlet, and oronasal mask were monitored for P_{O_2} and P_{CO_2} with a mass spectrometer. A small diameter gas sample line (i.d. 0.86 mm), as designed by Thalmann et al (3), resulted in little gas sample mixing and good frequency response, thereby allowing interpretation of end tidal P_{CO_2} values. In addition, diver heart rate, inspired gas temperature, and rectal temperature were monitored, and oronasal differential pressure was measured with a modified Validyne pressure transducer. These parameters were recorded on a Gould eight channel strip chart recorder.

Dive subjects exercised on a special underwater pedal ergometer (3) mounted on a vertical frame placed approximately ten feet underwater. Exercise schedules for canister duration and graded exercise studies were as outlined in Table 1. All measurements were made during the final minute of each exercise period, after steady state had been reached. It is probable that the actual work performed to overcome the combined resistance of the water, thermal garment, and ergometer was as much as 1.5 times the indicated load, as immersion has been estimated to increase the work of cycling by 25 to 50 watts depending upon the garment worn (4,5).

During graded exercise, the diver continued to exercise until he had completed the final work load or until he became fatigued. Work cycles less than 4 minutes in duration were not included in the data. Canister duration studies were terminated when canister effluent CO_2 reached 1% surface equivalent value (SEV). Canister breakthrough was defined as that point in time when canister effluent CO_2 reached 0.5% SEV.

All dive subjects wore the Mark 11 Mod 0 UBA with an umbilical length of 300 feet. Wet pot temperature was maintained within 2°F of 35°F (1.7°C). In order to duplicate situations of cold breathing gas, a special gas chiller at the umbilical source designed to cool inspired gas to near ambient tempe ture was used in all studies. Diver thermal protection was provided by an NRV hot water suit or a Mark 16 hot water suit with flow and temperature adjusted at 2.5 gallons per minute and not greater than 110°F (43.3°C) at the diver.

RESULTS

Figure 4 is a graphic depiction of typical canister breakthrough curves for the three tested canister configurations at a depth of 650 FSW. A typical curve for the central heated core configuration at 450 FSW is also shown in Figure 4. All of the curves are similar in shape, and differ only at the point in time at which peak canister effluent CO_2 levels with exercise begin to rise.

Table 2 tabulates the complete set of manned canister duration results for all canister configurations at both test depths. The modified canister with a central heated core had a mean duration of 308 ± 42 minutes at 450 FSW and 35°F (1.7°C) water temperature for six divers. This was significantly better than the standard canister, previously found to have a mean duration of 165 ± 23 minutes under the same test conditions. However, at 650 FSW and 35°F (1.7°C) water temperature, the central heated core configuration had a mean duration of 160 ± 62 minutes, which was only slightly higher than the standard canister configuration duration of 128 ± 36 minutes at 650 FSW. The triple pass canister at 650 FSW and 35°F (1.7°C) had the longest duration (271 ± 65 minutes), but the breathing resistance as measured by the oronasal differential pressure was excessively high and tended to increase as the canister became exhausted (Figure 5).

Figure 6 graphs mean canister duration versus depth for all canister configurations at 35°F (1.7°C). The triple pass canister was only tested at 650 FSW, and the data for the standard canister at depths shallower than 450 FSW is from a previous study (2). This graph, as well as Table 2, emphasizes the great variability in canister duration between individual divers at the same depths, and it shows the significant decrement in mean canister duration with increasing depth for the standard and central heated core canisters. Unmanned canister data indicates an additional 15-20% decrement in canister duration from 35°F to 30°F (-1.1°C) at the same test depths (6).

Table 3 is a summary of the graded exercise studies from all three dives. Peak end tidal P_{CO_2} values ($P_{ET_{CO_2}}$), oronasal differential pressures, inspired gas temperatures, and heart rates are tabulated for all canister configurations and work rates at both test depths.

Peak $P_{ET_{CO_2}}$, as illustrated by Figure 7, increased significantly at low work rates from rest levels and then tended to level off at higher work rates at 650 FSW. Peak $P_{ET_{CO_2}}$ was significantly higher for the triple pass canister than for the other two configurations at a given work rate. High minute ventilation did not result in elevated inspired P_{CO_2} secondary to inadequate gas residence time in the canister, as inspired P_{CO_2} did not exceed 0.4% SEV during graded exercise at either depth or for any canister configuration.

Figure 8 graphs oronasal differential pressure versus work rate for each canister at 650 FSW. Oronasal differential pressure increased with increasing work rate, and was so high in the triple pass canister that most divers could not complete the 150 watt work cycle. The oronasal ΔP for the central heated core canister was significantly less than for either of the other canisters at 650 FSW. However, direct comparison of breathing resistance between the central heated core canister and the other two canister configurations was not possible because FC 979A included both the low resistance Koegel valves and the central heated core. These two modifications were not man-tested independently. It should be noted, however, that only using this configuration were divers able to complete the 150 watt work cycles.

Mean resting inspired gas temperatures were 8 to 22°F above ambient water temperature, and increased by up to an additional 9°F during maximum work rates, with the central heated core canister providing the highest inspired gas temperatures. However, divers frequently complained of increased upper respiratory secretions, regardless of the canister type, and they attributed the symptoms to the cold breathing gas. Heat loss from the respiratory tract was probably substantial, but not sufficient to decrease rectal temperature during moderate leg exercise.

Inspired P_{O_2} varied between 1.2 and 0.4 ATA during graded exercise. The higher P_{O_2} occured during rest and gradually decreased to the lower value as work rate was increased from 50 to 150 watts.

DISCUSSION

The physiology of steady state exercise in diving is complicated by the effects of increased gas density and hyperoxia (7). Both of these conditions are associated with decreased ventilatory response to exercise and CO_2 retention at depth in divers even when they are not subject to increased external breathing resistance. Increased gas density increases external breathing resistance in any UBA, which tends to further depress ventilation.

If the ability of the diver to increase ventilation with an increase in metabolic CO_2 production is impaired, arterial and tissue P_{CO_2} rise. This can invoke a number of undesirable physiological responses including increased susceptibility to decompression sickness, oxygen toxicity, inert gas narcosis, reduced exercise capability, and depression of central nervous system function (5).

This problem of rising P_{CO_2} is demonstrable during graded exercise studies when $P_{ET_{CO_2}}$ rises to as much as 7.7% SEV at the 100 watt work load for the triple pass canister at 650 FSW (Figure 8). $P_{ET_{CO_2}}$ is felt to approximate arterial P_{CO_2}, although the $P_{ET_{CO_2}}-P_{a_{CO_2}}$ gradient in divers still requires investigation. Divers are capable of working with elevated P_{CO_2} levels, but the dyspnea associated with a given work load is generally greater than at normal P_{CO_2} levels, and end tidal P_{CO_2} levels of greater than 7% SEV are highly undesirable

In view of these physiological considerations, elevated inspired P_{CO_2} is hazardous to the diver. Arterial P_{CO_2} begins to rise in subjects performing light work in air at 1 ATA when inspired P_{CO_2} reaches 2.8% SEV (8). This data and the shape of the canister breakthrough curves (Figure 3) support the 0.5% SEV CO_2 canister breakthrough criterion, as canister effluent CO_2 levels rise at a markedly increased rate once this value is reached, and inspired P_{CO_2} could exceed 2.8% SEV within a few minutes. The graded exercise studies did not demonstrate high inspired P_{CO_2} at high work rates in any canister configuration, provided the CO_2 absorbent bed remained active. A high inspired P_{CO_2} during heavy exercise would have indicated inadequate gas residence time in the canister at high respiratory minute ventilation.

The Mark 11 canister life expectancy in all tested configurations is highly variable from diver to diver and decreases substantially with depth and cold. A significant improvement in canister duration offered by the central heated core canister configuration over the standard canister at 450 FSW is offset almost completely at 650 FSW. This may represent thermal failure of the scrubbing reaction due to the increased heat capacity of the dense helium at the deeper depth, as breathing gas temperatures are about the same for this canister configuration at both depths. Longer canister duration at 650 FSW is obtainable by using a three pass canister, however the breathing resistance is unacceptably high and tends to increase as the CO_2 absorbent is consumed.

Inspired gas temperatures in all tested configurations meet the minimum standards currently required by the U.S. Navy Diving Manual; however the central heated core canister provides significantly higher breathing gas temperatures than the other canisters. Respiratory heat loss is substantial but not sufficient to lower rectal temperatures in exercising divers at these test depths. Upper respiratory tract symptoms noted in some cases may not be solely attributable to cold inspired gas, as low inspired relative humidity may also contribute to these symptoms.

Overall improvement of the life support capability of the Mark 11 UBA is greatest when the central heated core canister and Koegel valves (FC 979A) are employed. In spite of marginal CO_2 scrubbing characteristics at 650 FSW, this canister offers a significant improvement in CO_2 scrubbing to depths of 450 FSW, as well as a varying CO_2 scrubbing advantage between 450 and 650 FSW if a linear interpolation is used. More importantly, FC 979A significantly lowers the breathing resistance of the Mark 11 system, and raises the breathing gas temperature to levels which enhance diver comfort and safety. However, because of the larger scatter in canister breakthrough data and limited sample size, it remains difficult to establish high confidence operational limits for the Mark 11 UBA, particularly at depths between 450 and 650 FSW.

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FIGURES AND TABLES

Type Of Study	Time	Work Rate	Duration
1. Canister duration	0-5 Min	Rest	5 Min
	5-11 Min	50 Watts	6 Min
	11-15 Min	Rest	4 Min
	15-21 Min	50 Watts	6 Min
	21-25 Min	Rest	4 Min
Work-Rest cycle continues until diver becomes fatigued or until the canister is exhausted (6 hour limit)			
2. Graded exercise	0-6 Min	Rest	6 Min
	6-12 Min	50 Watts	6 Min
	12-15 Min	Rest	3 Min
	15-21 Min	100 Watts	6 Min
	21-24 Min	Rest	3 Min
	24-30 Min	150 Watts	6 Min

TABLE 1 EXERCISE SCHEDULES FOR CANISTER DURATION AND GRADED EXERCISE STUDIES

DEPTH (FSW)	CANISTER CONFIGURATION AND CO_2 ABSORBENT	DIVER	CANISTER DURATION (Min to 0.5% CO_2 SEV)
450	Unmodified Canister†	1	165
	*18% Moisture HP Sodasorb	2	150
		3	165
		4	130
		5	185
		6	195
		Mean ± SD	165 ± 23
450	Modified Canister	1	280
	with central heated core	2	370
	standard HP Sodasorb	3	305
		4	345
		5	280
		6	265
		Mean ± SD	308 ± 42
650	Unmodified Canister	1	94
	*18% Moisture HP Sodasorb	3	107
		4	175
		6	137
		Mean ± SD	128 ± 36
650	Modified Canister	1	205
	Triple Pass	3	262
	*18% Moisture HP Sodasorb	4	258
		6	360
		Mean ± SD	271 ± 65
650	Modified Canister	1	147
	with central heated core	2	150
	standard HP Sodasorb	3	210
		4	60
		5	240
		6	155
		Mean ± SD	160 ± 62

TABLE 2: TABULATION OF MANNED MARK 11 CANISTER DURATION STUDIES
Wet Pot Water Temperature 36° ± 1°F and Canister Inlet Hot Water Temperature 108 ± 2°F for all studies.

† Data from Reference (2)
*High moisture sodasorb does not improve manned canister duration significantly.

Parameter	Canister Configuration	Depth	Rest	50	100	150
			Work Rate (Watts)			
Peak End Tidal	Central Heated	450	5.0 ± 0.2	6.3 ± 0.5	6.7 ± 0.5	7.2 ± 0.6
CO_2 %SEV	Core (FC 979A)	650	4.8 ± 0.2	6.4 ± 0.6	6.9 ± 0.7	7.4 ± 1.2
(Mean ± SD)	Triple Pass	650	5.9 ± 0.7	7.6 ± 0.7	7.7 ± 1.0	—
	Standard	650	5.4 ± 0.8	6.9 ± 0.7	7.0 ± 0.6	—
Oronasal	Central Heated	450	12 ± 2	18 ± 2	[illegible]1 ± 2	26 ± 5
Differential	Core (FC 979A)	650	12 ± 1	20 ± 2	24 ± 2	26 ± 4
Pressure cm H_2O (Mean ± SD)	Triple Pass	650	16 ± 2	39 ± 5	44 ± 3	—
	Standard	650	16 ± 2	27 ± 2	32 ± 2	—
Inspired Gas	Central Heated	450	59 ± 4.0	59 ± .0	59 ± 4.0	60 ± 3.3
Temperature (°F)	Core (FC 979A)	650	53 ± 0.5	59 ± 2.8	61 ± 1.0	60 ± 4.2
(Mean ± SD)	Triple Pass	650	44 ± 1.0	44 ± 1.0	45 ± 3.0	—
	Standard	650	43 ± 1.0	47 ± 1.5	49 ± 3.0	—
Heart Rate	Central Heated	450	85 ± 7	121 ± 6	140 ± 10	155 ± 10
beats/min	Core (FC 979A)	650	90 ± 11	125 ± 12	148 ± 13	162 ± 9
(Mean ± SD)	Triple Pass	650	89 ± 8	129 ± 3	157 ± 6	—
	Standard	650	85 ± 6	116 ± 5	135 ± 10	—

TABLE 3: TABULATION OF MARK 11 GRADED EXERCISE WITH DIFFERENT CANISTER CONFIGURATIONS

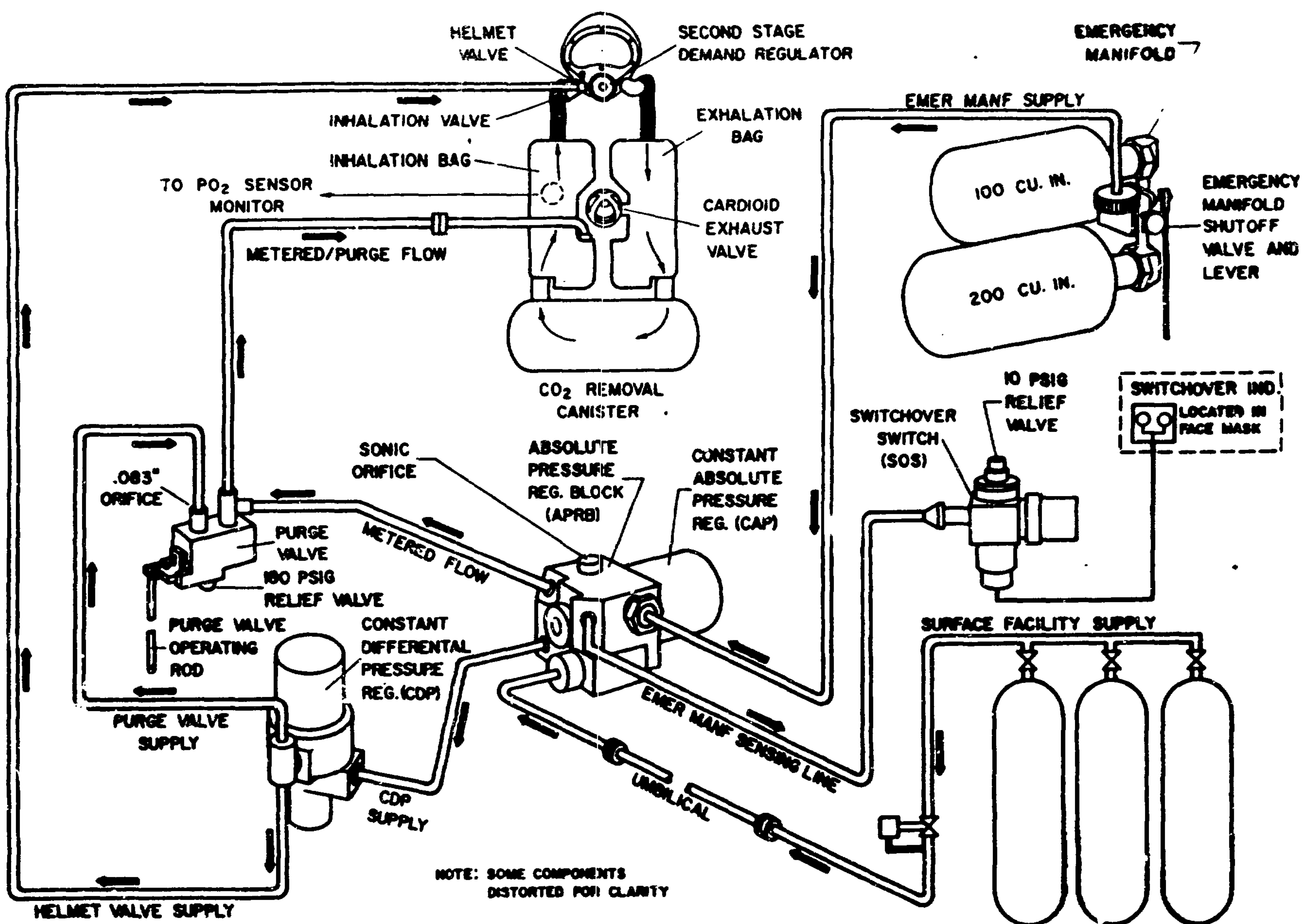

FIGURE 1. MARK 11 BREATHING SUBSYSTEM

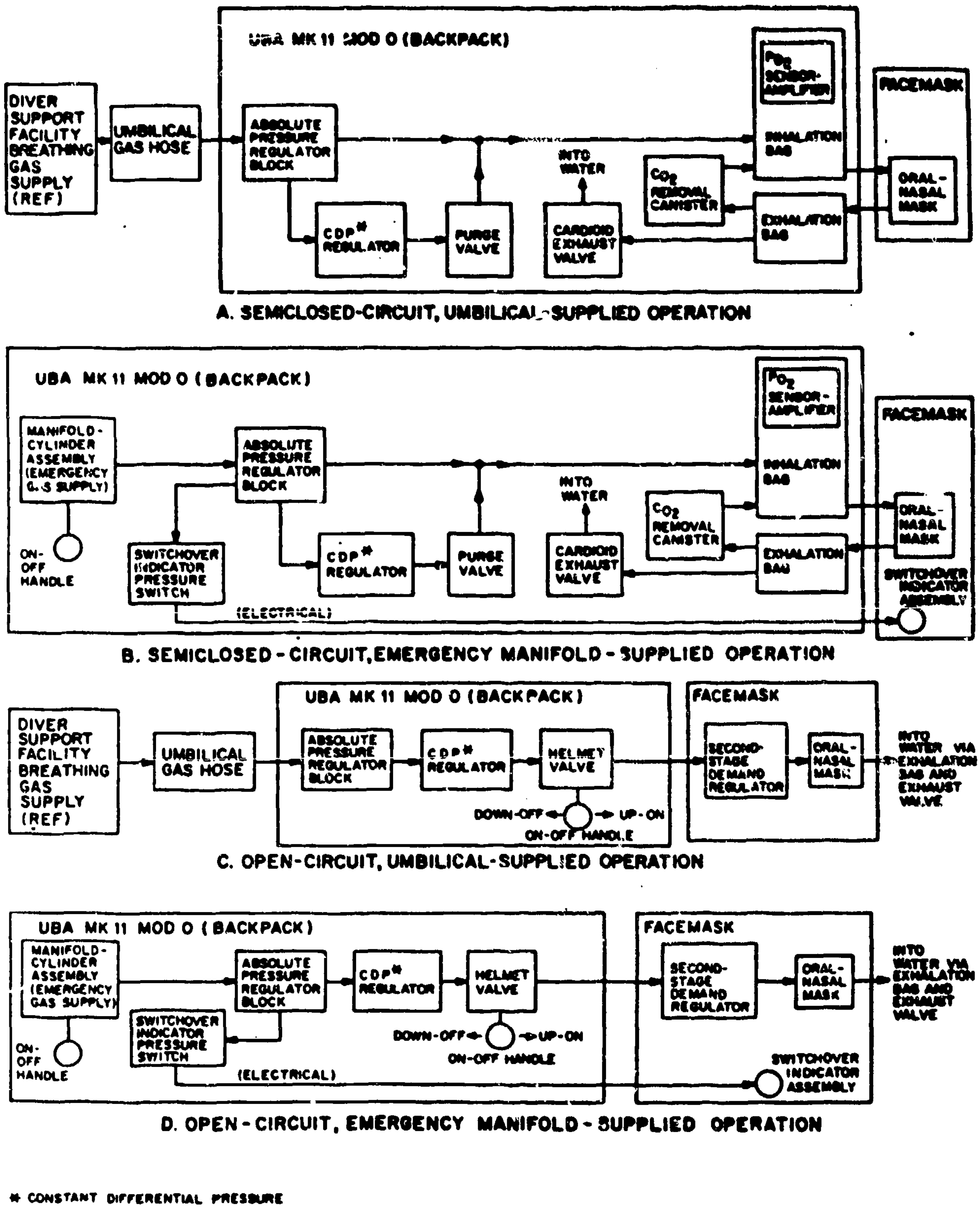

FIGURE 2. GAS FLOW DIAGRAM IN EACH OPERATING MODE

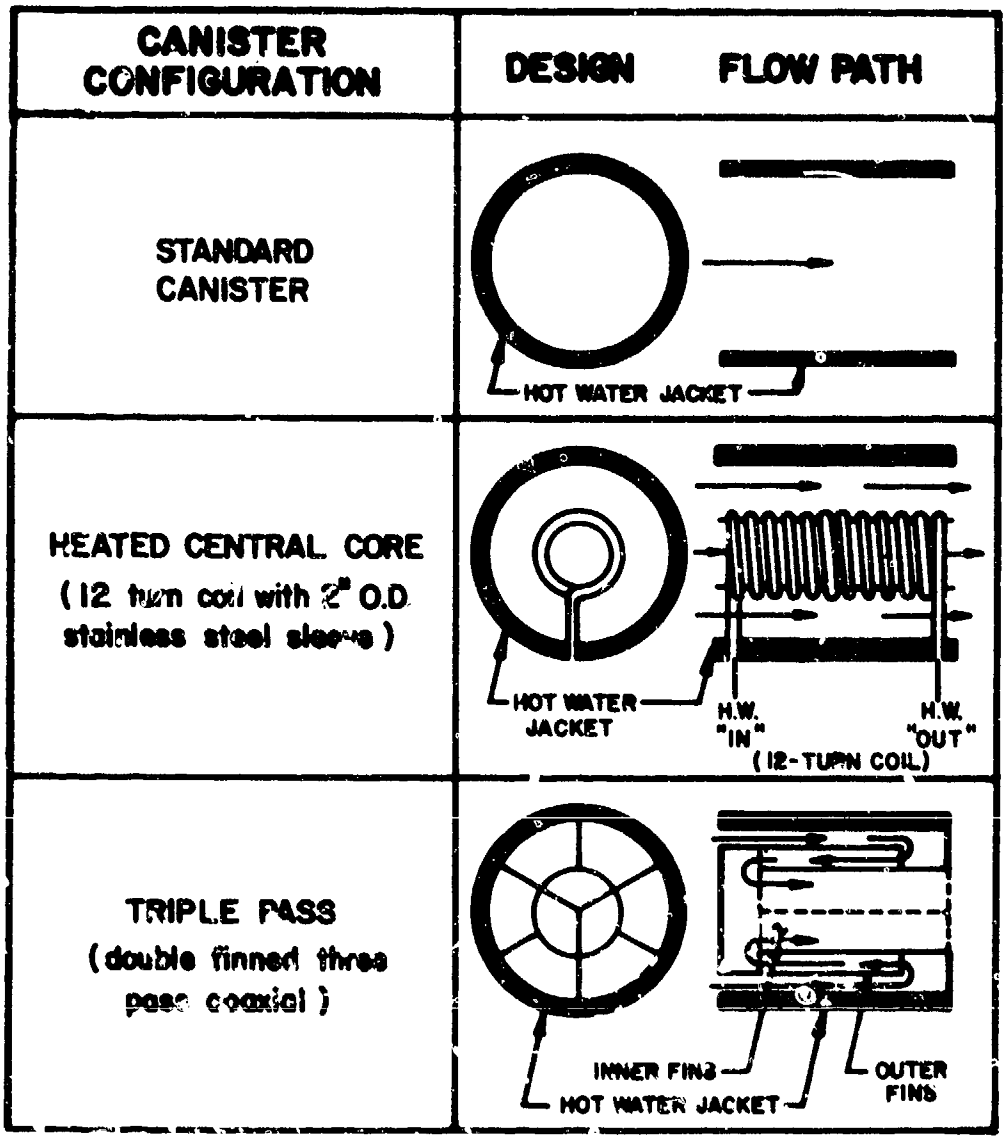

FIGURE 3. MARK 11 CANISTER CONFIGURATIONS TESTED DURING MANNED EVALUATIONS

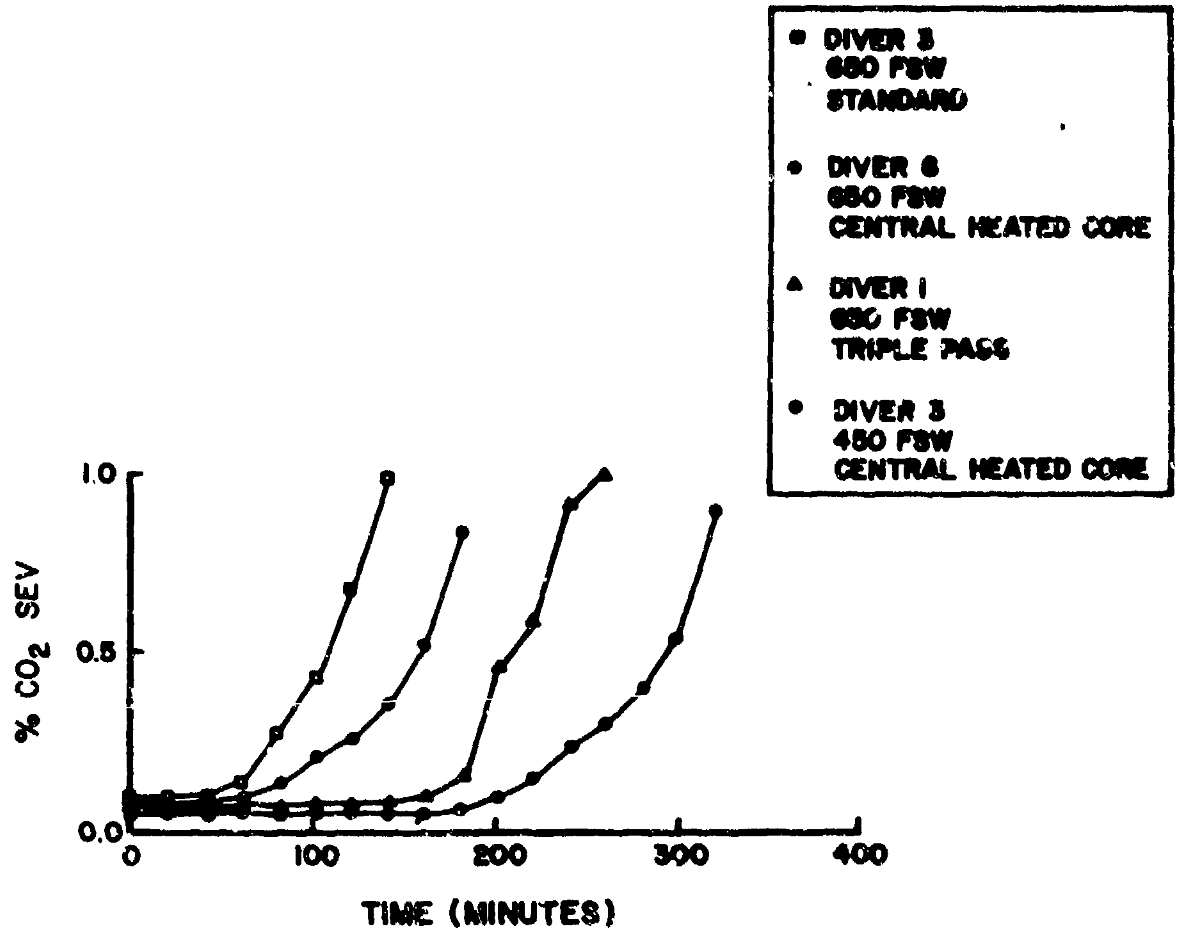

FIGURE 4: TYPICAL CANISTER BREAKTHROUGH CURVES FOR DIFFERENT MARK II CANISTER CONFIGURATIONS.

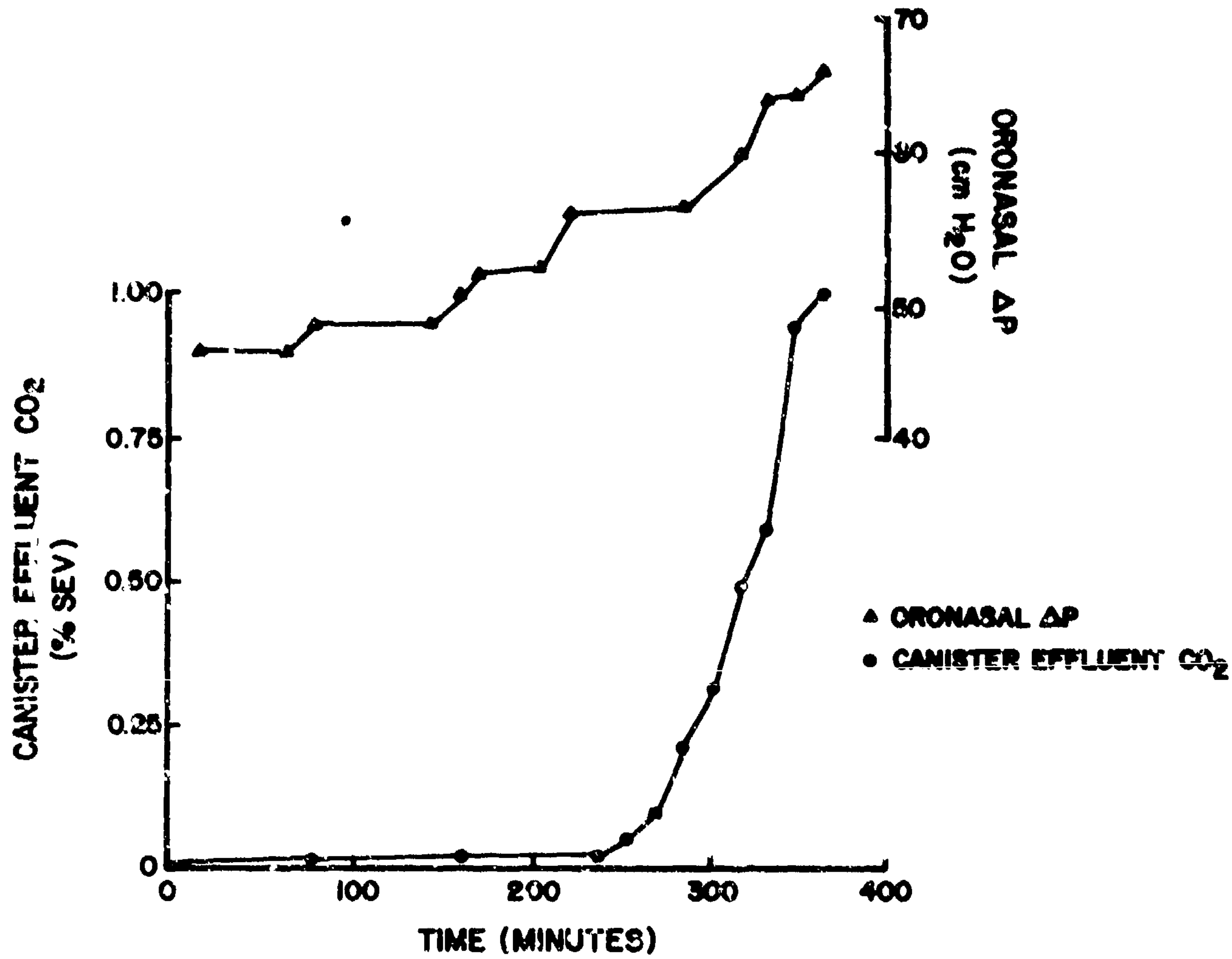

FIGURE 5: CANISTER EFFLUENT CO_2 AND ORONASAL ΔP VS TIME FOR TRIPLE PASS MK II CANISTER AND DIVER I AT 650 FSW.

CANISTER CONFIGURATION	DEPTH (FSW)	MEAN DURATION ± 1SD (MINUTES)
UNMODIFIED ○	310	270 ± 50
	350	221 ± 65
	450	165 ± 23
	650	128 ± 36
CENTRAL HEATED CORE ●	450	308 ± 42
	650	160 ± 65
TRIPLE PASS ▲	650	271 ± 65

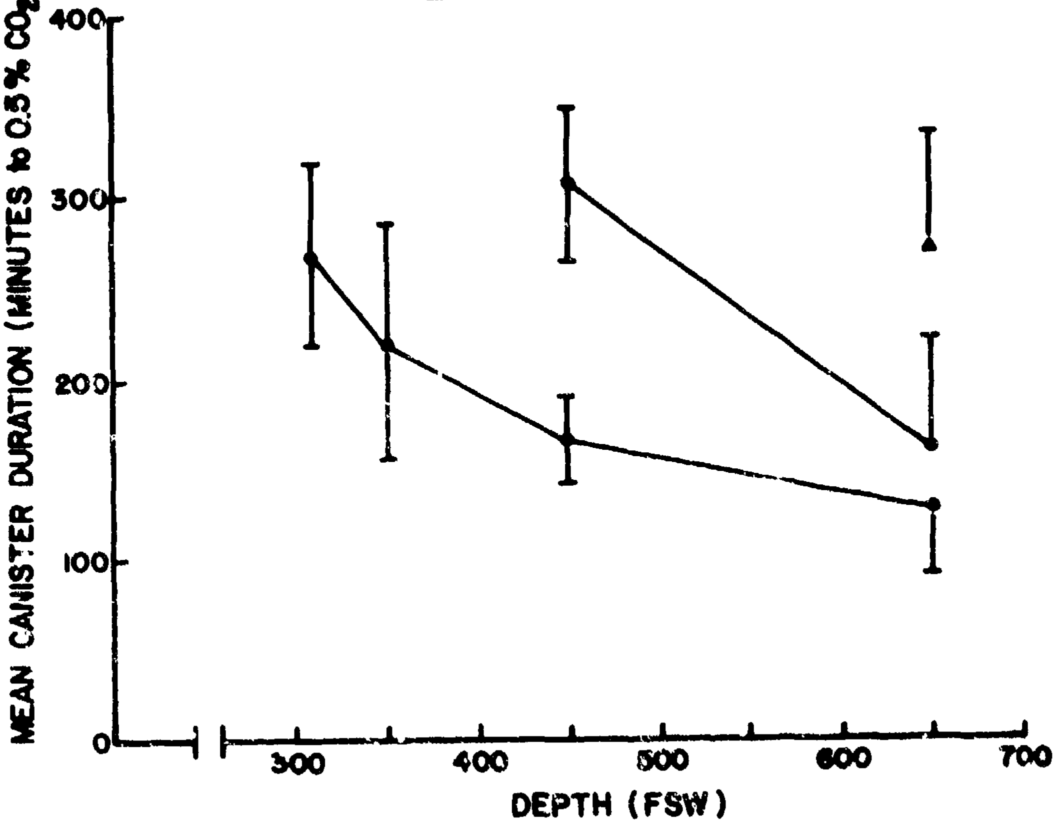

FIGURE 6: MEAN CANISTER DURATION VERSUS DEPTH

18% MOISTURE HP SODASORB AT 35° F (1.7 °C) AND CANIS...R INLET HOT WATER TEMPERATURE 108 ± 2°F (42.2 ± 1.1°C).

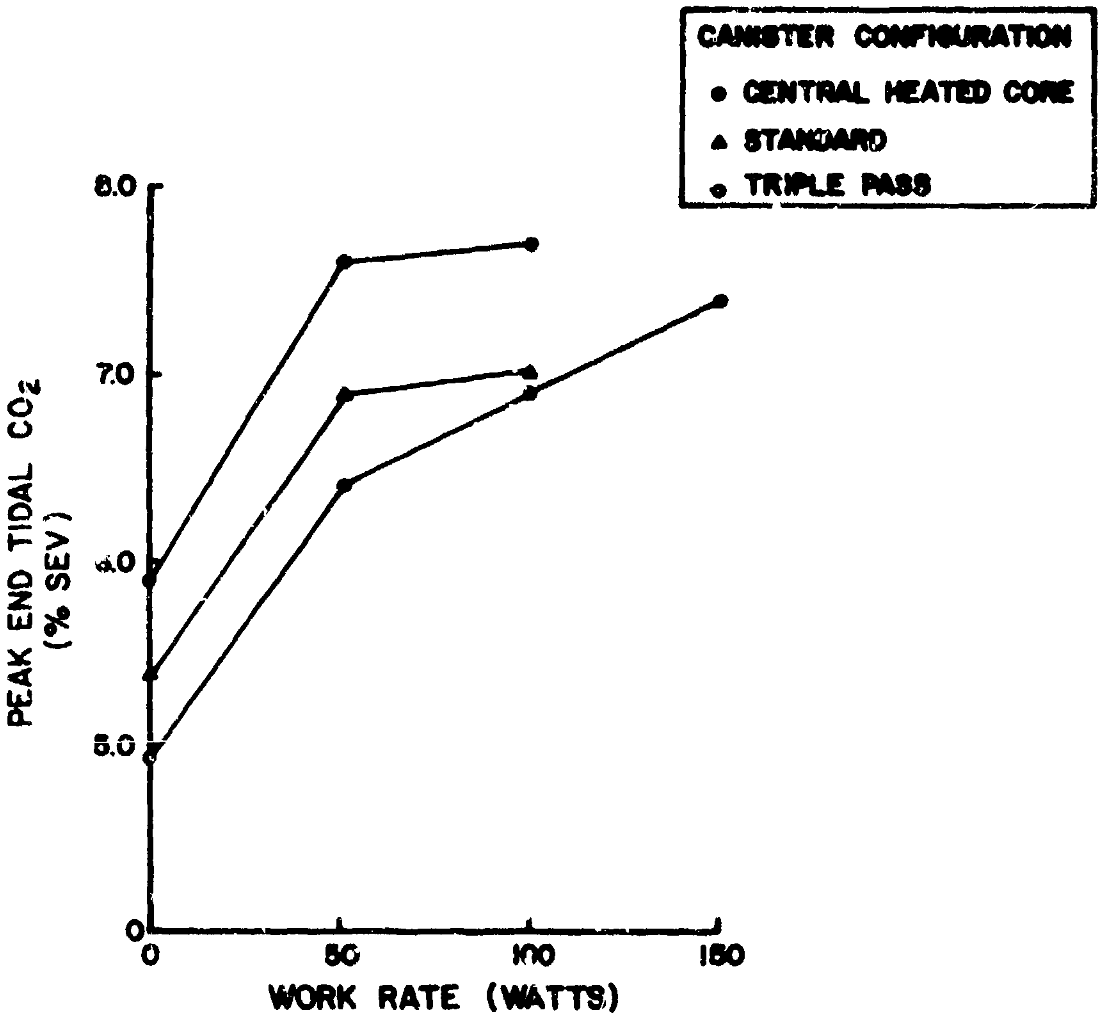

FIGURE 7: PEAK END TIDAL CO_2 VERSUS WORK RATE AT 650 FSW.

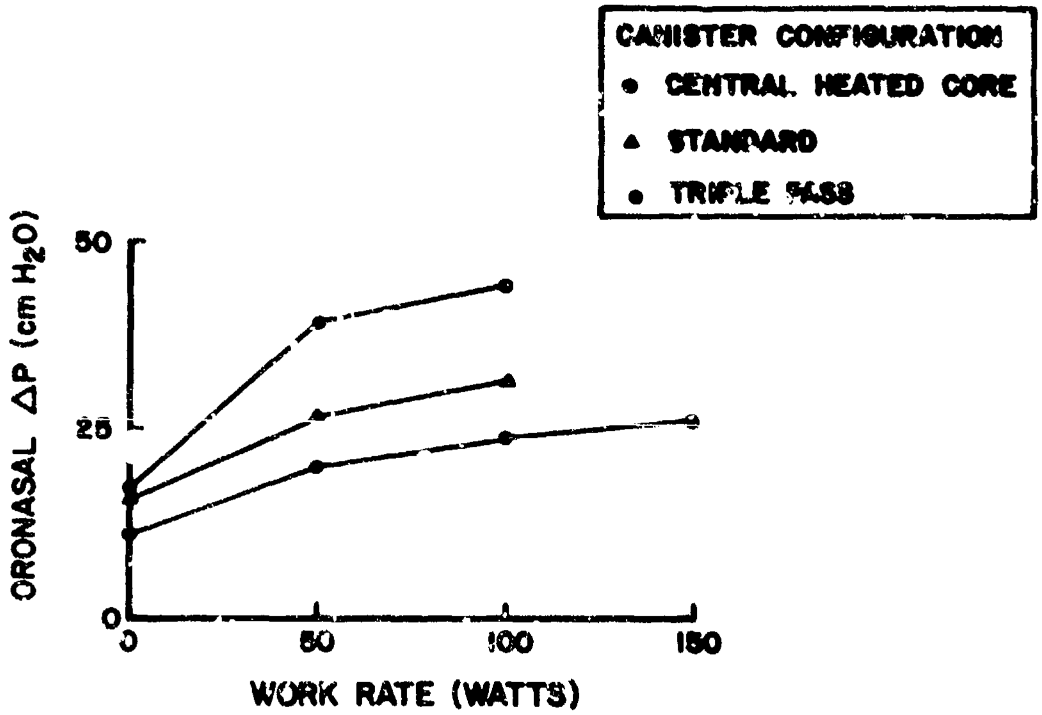

FIGURE 8: ORONASAL ΔP VERSUS WORK RATE AT 650 FSW.